

LETTER TO THE EDITOR

# Smooth X-ray variability from $\rho$ Ophiuchi A+B.

## A strongly magnetized primary B2 star?

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### ABSTRACT

X-rays from massive stars are ubiquitous yet not clearly understood. In an *XMM-Newton* observation devoted to observe the first site of star formation in the  $\rho$  Ophiuchi dark cloud, we detect smoothly variable X-ray emission from the B2IV+B2V system of  $\rho$  Ophiuchi. Tentatively we assign the emission to the primary component. The light curve of the *pn* camera shows a first phase of low, almost steady rate, then a rise phase of duration of 10 ks, followed by a high rate phase. The variability is seen primarily in the band 1.0–8.0 keV while little variability is detected below 1 keV. The spectral analysis of the three phases reveals the presence of a hot component at 3.0 keV that adds up to two relatively cold components at 0.9 keV and 2.2 keV. We explain the smooth variability with the emergence of an extended active region on the surface of the primary star due to its fast rotation ( $v \sin i \sim 315$  km/s). We estimate that the region has diameter in the range 0.5 – 0.6  $R_*$ . The hard X-ray emission and its variability hint a magnetic origin, as suggested for few other late-O–early-B type stars. We also discuss an alternative explanation based on the emergence from occultation of a young (5–10 Myr) low mass companion bright and hot in X-rays.

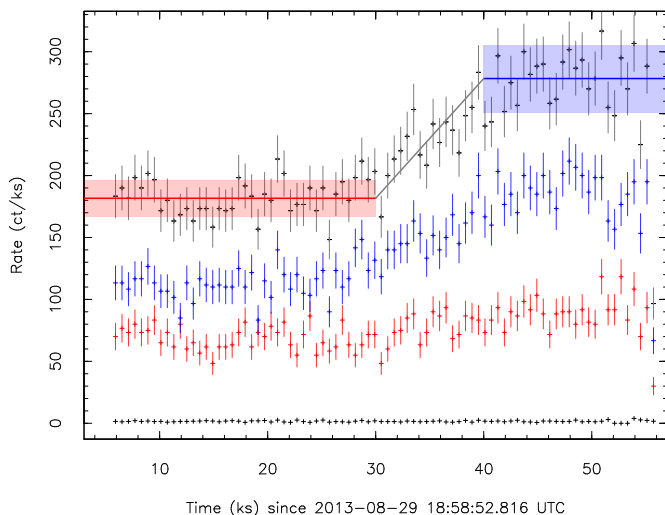
**Key words.** stars: activity – stars: individual (Rho-Ophiuchi) – stars: early-type – stars: magnetic field – stars: starspots

### 1. Introduction

X-ray emission is a common feature among massive stars of spectral type O through early B-type. In single O-stars, a soft X-ray emission is thought to be generated by shocks in the stellar winds accelerated by the strong X-UV stellar flux in a non linear mechanism called Line De-shadowing Instability (LDI, Owocki et al. 1988; Feldmeier et al. 1997a,b). In strongly magnetized massive early-type stars, winds can be channeled and collide at high Mach numbers generating hard X-ray emission (Babel & Montmerle 1997; ud-Doula & Owocki 2002). In binary systems, large-scale shocks associated with wind-wind collisions can manifest themselves in additional X-ray emission (Stevens et al. 1992). Examples of variability from colliding winds on a time scale of a few years synchronized with the orbital period of O-type binaries are observed in three systems of the Cyg OB2 complex (Cazorla et al. 2014).

The origin of magnetic fields in O and B stars is thought to reside either in a dynamo mechanism at the interface between convective core and radiative layers (but it is still difficult to model the buoyancy of the magnetic field), or it has a fossil origin being the ambient magnetic field from the parent cloud trapped and compressed during the formation of the star, with some subsequent dynamo driven amplification (Walder et al. 2012). In both cases, the magnetic fields likely have a main dipolar component although more complex configurations can be present. In this framework, the origin of X-rays from stellar winds is less probable in B type stars because of their weaker winds with respect to those of O and WR stars. The rate of detection in X-rays among B stars falls to about 50% (Wolk et al.

2011; Nazé et al. 2011; Rauw et al. 2014) and hard X-ray emission in a few cases are a signature of the presence of strong magnetic fields. Significant examples of X-ray emitters among late O- early B type stars are given by  $\tau$  Sco (Cohen et al. 2003),  $\beta$  Crucis (Cohen et al. 2008),  $\zeta$  Puppis (Nazé et al. 2013), and  $\theta^1$  Ori C (Gagné et al. 1997). The detection of spots on the surface of late O / early B-type stars have been reported in X-ray band by Gagné et al. (1997) on  $\theta^1$  Ori C (O7 V, rotation period  $p = 15.4$ ) with *ROSAT*, and recently by Fossati et al. (2014) in two early B-type stars of the NGC 2264 star forming region. Another case of modulated variability and hard X-ray spectrum in early B star which hints a magnetic origin is  $\sigma$  Ori E (Skinner et al. 2008). Here we report on X-rays from  $\rho$  Ophiuchi, a binary system at a distance of  $\sim 111$  pc from the Sun, composed of a B2IV star and a B2V star (Abt 2011; van Leeuwen 2007). The separation between the two stellar components is about  $2.8''$  or 310 AU at a distance of 111 pc, and the orbital period is  $\sim 2000$  years.  $\rho$  Ophiuchi sits about 1 deg north of the dense core of active star formation L 1688, and gives it the name “the  $\rho$  Ophiuchi dark cloud complex”. About 300 members in various stages of formation - from Class 0/I to Class II and III - belong to L 1688 (Wilking et al. 2008) at an average distance of 120 – 130 pc. A ring of dust visible in far to mid infrared and with radius  $\sim 40'$  (1.4 pc) surrounds  $\rho$  Ophiuchi and possibly formed by the winds of the central binary system. In this area a number of Pre Main Sequence stars have formed likely coeval to  $\rho$  Ophiuchi. We observed  $\rho$  Ophiuchi with *XMM-Newton* for a duration of  $\sim 53$  ks in order to identify and to study this first episode of star formation likely triggered by  $\rho$  Ophiuchi system itself. Indeed, we discovered a group of about 25 young low mass stars around



**Fig. 1.** *pn* light curve of  $\rho$  Ophiuchi in broad band (0.3-8 keV), hard band (blue,  $> 1$  keV), soft band (red,  $< 1.0$  keV), and background. The events are extracted from a circular region centered on the X-ray centroid position (see Table 1) and of radius  $16''$ . We observe three phases in  $\rho$  Ophiuchi's curve: a low rate phase (0–30 ks), a rise phase (30–40 ks) and a high rate phase ( $> 40$  ks). The rate in the quiescent phase has a median value of  $\sim 182$  ct/ks with a mean absolute deviation (MAD, marked with the red shaded area) of 15 ct/ks. High phase rate has a median rate of 280 ct/ks with MAD = 27 ct/ks (blue shaded area). The change in the rate is mostly seen above 1 keV, while the soft band rate remains almost constant.

**Table 1.** Optical positions of the components of  $\rho$  OphiuchiA+B system and of the X-ray centroid.

Object	R.A. (FK5, J2000)	Dec. (J2000)
$\rho$ Ophiuchi A	$16^h25^m35.118^s$	$-23^d26^m49.81^s$
$\rho$ Ophiuchi B	$16^h25^m35.05^s$	$-23^d26^m46.0^s$
X-ray centroid	$16^h25^m35.2^s$	$-23^d26^m48.3^s$

$\rho$  Ophiuchi that are older ( $\sim 5$  Myr, Pillitteri et al., in preparation) than the embedded population in L1688 ( $< 1$  Myr).

## 2. X-ray light curve and spectra

The *XMM-Newton* observation was taken on August 29th 2013, for a nominal duration of  $\sim 53$  ks. The *Thick* filter was used for the EPIC exposures in order to prevent damage to the instruments and to avoid UV contamination from  $\rho$  Ophiuchi, which has magnitude  $V = 5.05$ . The data sets were analyzed with SAS version 13.5, starting from the Observation Data Files and reducing them to obtain calibrated event lists in 0.3–8.0 keV band for MOS and *pn* cameras, including a filtering of events for PATERN  $< 4$  and FLAG  $< 0$ .

We detected copious X-ray emission from the  $\rho$  Ophiuchi system. Given the spatial resolution of the EPIC camera and the errors associated to the positions of the X-ray sources we cannot firmly distinguish between the X-ray emission of  $\rho$  Ophiuchi A and B (see Table 1 for the positions of the components of  $\rho$  Ophiuchi system). The *Point Spread Function* (PSF) of EPIC is about  $4.4''$  (FWHM), the calibration of absolute astrometry has nominally zero systematic shift and less than  $0.8''$  of error. Relative astrometry of EPIC has uncertainties of less than  $1.2''$ . The positional uncertainty for  $\rho$  Ophiuchi from the wavelet detection code (Damiani et al. 1997b,a) is  $< 1''$ . We expect that the

combination of these source of astrometric uncertainties amount to  $\leq 2''$ . A visual inspection of the MOS 1 image shows that the centroid of the emission is closer to the optical position of  $\rho$  Ophiuchi A (Fig. 2), thus we tentatively assign the X-ray emission and its features to the primary star.

$\rho$  Ophiuchi has been observed with *XMM-Newton* without interruptions for about 53 ks. The background rate was generally low, but elevated during the last 5 ks. Data acquired during the high background interval were filtered out only for improving the source detection process and to maximize the signal to noise of faintest sources. Here we considered the full length exposure. In the *pn* light curve of  $\rho$  Ophiuchi we recognize three phases (Fig. 1). A first phase of relatively low rate (median *pn* rate: 182 ct/ks, median MOS 1 rate:  $62 \pm 12$  ct/ks; median MOS 2 rate:  $63 \pm 12$  ct/ks, all rates given in 0.3-8.0 keV band), a second phase of gradual increase of the rate lasting about 10 ks, then a phase of high rate (median *pn* rate 280 ct/ks; median MOS 1 rate:  $95 \pm 12$  ct/ks; median MOS 2 rate:  $91 \pm 6$  ct/ks, all rates given in 0.3-8.0 keV band). Small flickering at level of one sigma is visible on top of the average flux during the whole observation. The light curves in soft (0.3–1.0 keV) and hard ( $> 1$  keV) bands show that the increase of flux is smooth essentially observed in the hard band.

We have analyzed the MOS 1, MOS 2 and *pn* spectra from the time interval in 0–30 ks, 30–40 ks and 40–60 ks in order to identify spectral changes. The best fit parameters are shown in Table 2. During the initial low rate phase, a best fit to the spectrum is obtained with a sum of two thermal APEC components plus global absorption. The temperatures are  $kT_1 = 0.9$  keV and  $kT_2 = 2.2$  keV with the hot component accounting for about 30% of the total plasma emission measure.

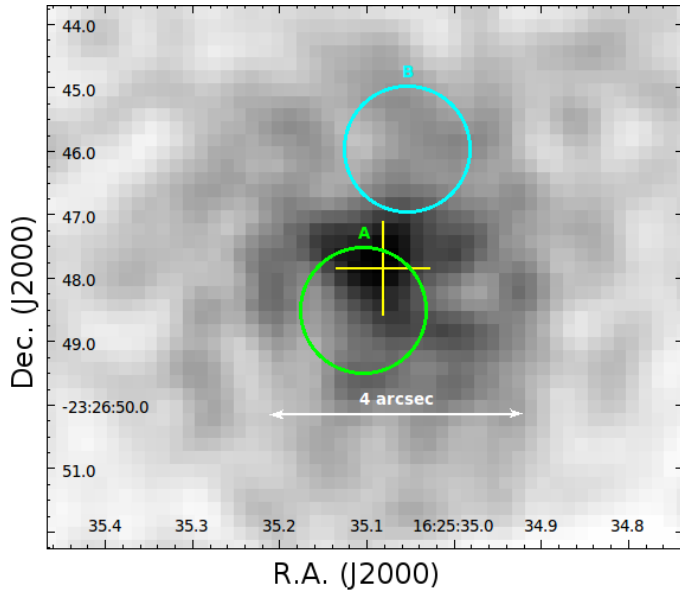
For the best fit of the rise and the high rate phases, we have added a third component to the 2T model used for the low rate spectrum. Our hypothesis is that a hot component appears gradually on the visible face of the star during the rise, and remains visible during the high rate phase. The two components of the low rate phase were kept fixed while we allowed to vary only the hot component temperature, and its normalization. Plasma as hot as 3.0-3.4 keV is found during the rise and the high rate phase. The temperatures of the third hot component, estimated during rise and high rate intervals, are consistent with each other within one  $\sigma$  reinforcing the scenario of a hotter region emerging in the visible part of the primary star. The change of flux is manifested by a gradual increase of the emission measure of the hot plasma component, which increases from  $5.1 \times 10^{52} \text{ cm}^{-3}$  to  $9.7 \times 10^{52} \text{ cm}^{-3}$ . This is fully compatible with the hypothesis of a region brighter and hotter than the average stellar surface that gradually appears on view during the rise of the count rate. The flux varies by a factor 40% going from low rate to high rate phases.

Compared to the B stars in Carina region,  $\rho$  Ophiuchi is quite peculiar with regard to its X-ray properties. Gagné et al. (2011) find that B stars in Carina with X-ray luminosity higher than  $L_X \geq 10^{31} \text{ erg s}^{-1}$  have a hard spectrum ( $kT > 1$  keV) while B stars with  $L_X < 10^{31} \text{ erg s}^{-1}$  have softer spectra ( $kT < 0.6$  keV). Despite its relatively low X-ray luminosity ( $L_X \sim 10^{30} \text{ erg s}^{-1}$ ), the spectrum of  $\rho$  Ophiuchi is quite hard during the low rate phase ( $kT_2 \sim 2$  keV) and becomes even harder during the rise and high rate phase ( $kT_3 \sim 3.0 - 3.4$  keV).

Stelzer et al. (2005) report the case of three late O / early B type stars from the COUP sample that exhibit periodic X-ray variability phased with the rotational stellar period. The hardness ratios of these stars are periodic as well with the hardest spectrum corresponding to the highest rate as we find in  $\rho$  Ophiuchi.

**Table 2.** Parameters from model best fit to the  $pn$  spectra in the three different temporal phases. Parameters kept fixed in rise and high rate phases are enclosed in braces.

Parameters:	Phase:		
	Low Rate	Rise	High Rate
$\chi^2$	124.1	89.4	208.6
D.o.F.	134	99	147
$N_H$ (cm $^{-2}$ )	0.33 $\pm$ 0.02	0.32 $\pm$ 0.03	0.31 $\pm$ 0.07
$kT_1$ (keV)	0.9 $\pm$ 0.03	(0.9)	(0.9)
Abundance (Z/Z $_{\odot}$ )	0.13 $\pm$ 0.02	(0.13)	(0.13)
$EM_1$ (10 $^{52}$ cm $^{-3}$ )	21.8 $\pm$ 0.7	(21.8)	(21.8)
$kT_2$ (keV)	2.1 $\pm$ 0.4	(2.1)	(2.1)
$EM_2$ (10 $^{52}$ cm $^{-3}$ )	7.8 $\pm$ 2.9	(7.8)	(7.8)
$kT_3$ (keV)	–	3.4 $\pm$ 0.5	3.0 $\pm$ 0.3
$EM_3$ (10 $^{52}$ cm $^{-3}$ )	–	5.1 $\pm$ 0.7	9.7 $\pm$ 0.7
Flux (10 $^{-12}$ erg s $^{-1}$ cm $^{-2}$ )	1.50	1.88	2.2



**Fig. 2.** Mos 1 image and positions of the two components of  $\rho$  Ophiuchi system, A and B. The original image is binned in blocks of size  $0.2'' \times 0.2''$ , and smoothed with a gaussian kernel of 3 pixels. The color scale is linear. The cross marks the position of the X-ray centroid and gives a visual estimate of the positional uncertainty. The circles have radii of  $1''$  to account for the precision of the optical positions. Although we cannot separate X-ray emission of both components, the centroid of the emission appears closer to the A component.

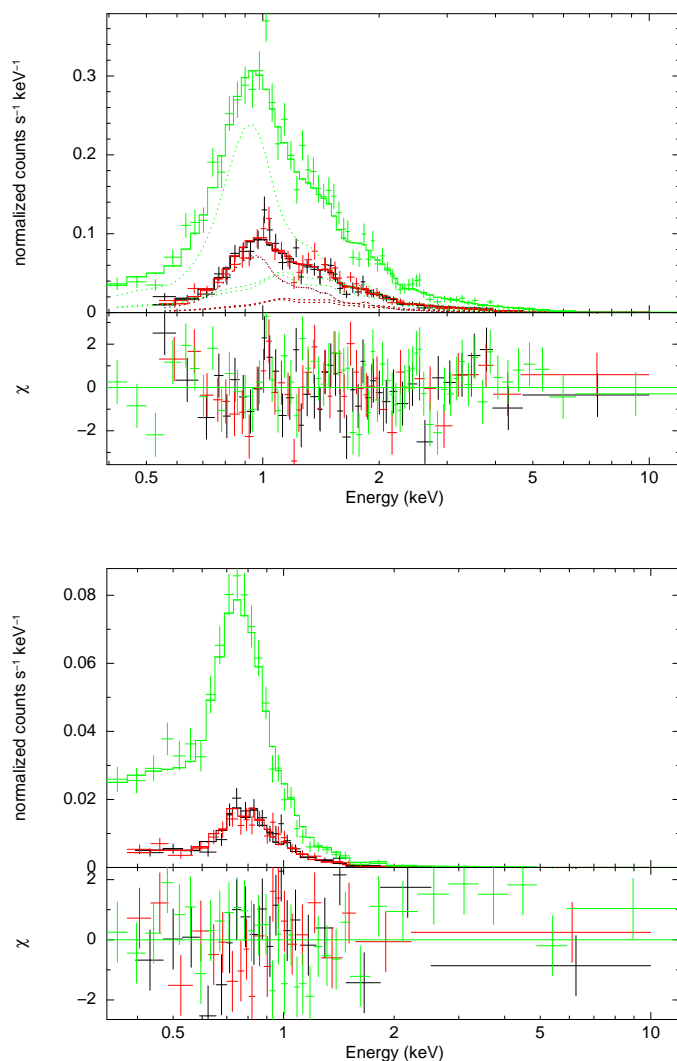
For further comparison, we have analyzed the EPIC spectra of HIP 100751 ( $\alpha$  Pavonis) which is also a B2IV type star in a binary system and recently observed by *XMM-Newton* (ObsId: 0690680201, PI: W. Waldron). The light curve of HIP 100751 shows brief impulsive variability, more typical of young solar mass stars, and perhaps originated by the unresolved stellar companion. The spectrum of HIP 100751 is quite soft (Fig. 3, bottom panel), the best fit is obtained with two thermal APEC components at  $kT_1 = 0.4$  keV and  $kT_2 = 0.8$  keV, with the cold component emission measure being the 70% of the total emission measure, and the total X-ray luminosity is  $2.6 \times 10^{28}$  erg s $^{-1}$  in 0.3–8.0 keV band. We conclude that  $\rho$  Ophiuchi is thus more luminous than HIP 100751 and it has a harder spectrum, reinforcing the peculiarity of  $\rho$  Ophiuchi.

### 3. Discussion and conclusions

The X-ray variability and the hardness of the X-ray spectrum of  $\rho$  Ophiuchi make this star interesting in the context of X-ray emission from massive stars. We have observed  $\rho$  Ophiuchi in X-rays with *XMM-Newton* and we found a smooth increase of the X-ray flux above 1 keV. We tentatively assign the whole X-ray emission to the primary component given the shorter distance of the X-ray flux centroid from its optical position. However, the low spatial resolution of the EPIC camera compared to the separation of the two components of the system ( $\sim 2.8''$ ) does not determine precisely the source of X-rays.

We observe a low rate phase followed by a smooth rise and a high rate state. A first possible interpretation of this behaviour is that the increase of rate as due to a hot active region emerging from the limb on the stellar surface because of the rotation of the star. We measured the rotational broadening  $v \sin i$  of  $\rho$  Ophiuchi A from the width of the He I line at 6678Å in an archival UVES spectrum, obtaining a value of  $v \sin i \sim 315$  km/s in agreement with literature values ( $v \sin i \sim 300$  km/s). Given a duration of the rise phase of about 10 ks, we estimated a diameter of the active region on the equator of the star of about  $3.15 \times 10^6$  km. This size corresponds to about  $0.5 - 0.6 \times R_*$ , and thus the active region is quite large. The active region could be at the equator or at any higher stellar latitude and its origin is likely due to a strong magnetic field. If the magnetic field has a main dipolar shape then an oblique magnetic rotator is involved and the spot is at high latitude. Were the spot at the equator, a more complex toroidal field has to be involved.  $\rho$  Ophiuchi is not the first case of spotted B stars as we observed before, as spots have been identified in other O-late and B-early stars, e.g. two young B2 stars in NGC 2264 (Fossati et al. 2014). In these latter cases, the magnetic origin of the surface spots is inferred by means of spectropolarimetric observations, with magnetic fields of a few hundreds of Gauss of intensity and configurations as simple and double dipoles, respectively. Fossati et al. (2014) discuss the origin of such magnetic fields, preferring the hypothesis of a merging event during the star formation rather than a fossil origin. The relevance of  $\rho$  Ophiuchi in this context is that its close distance allows detailed further investigations.

Another explanation for the smooth variability is that a low mass unknown companion of  $\rho$  Ophiuchi A appears to view and bearing an additional flux with intrinsic harder emission. The companion could emerge from behind the primary accounting for the rise phase during the two limb contacts. Given the difference of flux between low and high state, its luminosity should be  $L_X \sim 1.1 \times 10^{30}$  erg s $^{-1}$ , which is on the median X-ray luminosity of young stars bright in X-rays that we detected around  $\rho$  Ophiuchi (median  $L_X \sim 1.25 \times 10^{30}$  erg s $^{-1}$ ). In a simplistic hypothesis, at 1 AU the keplerian orbital velocity is  $\sim 89$  km s $^{-1}$ , and considering a 10 ks time for the full disk appearance, a radius of  $0.6 R_{\odot}$  is derived. The radius of the companion is inversely proportional to the period (i.e. if  $r = 0.5 R_{\odot}$ ,  $P \approx 50$  days), while its mass does not play a role. Very little constraint on mass and radius comes from the value of X-ray luminosity that this companion should bear ( $L_X = 1.1 \times 10^{30}$  erg s $^{-1}$ ). Because of the saturation of  $L_X$  expected at this age (5–10 Myr) for  $G - K$  type stars (Pizzolato et al. 2003; Jardine & Unruh 1999; Favata & Micela 2003) the presence of a relatively small companion like a K early type star is plausible. A very close companion coeval of  $\rho$  Ophiuchi should experience its X-ray luminosity enhanced by the likely spin-orbit locked rotation and thus values of  $L_X \sim 10^{30}$  erg s $^{-1}$  could be observed in such object. A main drawback for this scenario is the lack of enhancement of the soft emission (e.g.



**Fig. 3.** Top figure: EPIC MOS 1 (black), MOS 2 (red) and *pn* (green) spectra of  $\rho$  Ophiuchi during the high rate phase (top panel) and  $\chi^2$  terms (bottom panel). Dotted lines The APEC components are plotted along with the data. A high temperature of  $\sim 3$  keV is detected during the rise and the high rate phase. Bottom figure: same plot for HIP 100751. Notice the harder spectrum of  $\rho$  Ophiuchi compared to HIP 100751. The spectra are accumulated from the same events selected for the light curve (see Fig. 1).

below 1 keV) due to the unknown companion (see Fig. 1). It is quite unlikely that the spectrum of this stellar object is hard or it is heavily absorbed by intervening material. The absorption toward  $\rho$  Ophiuchi is indeed quite moderate ( $N_H \sim 3.4 \times 10^{21} \text{ cm}^{-2}$ ) and soft emission during the low state interval is detected.

$\rho$  Ophiuchi could be similar to the very young system of Oph S 1, which is likely constituted by a B type star and an unknown low mass companion. Oph S 1 is known to emit variable X-rays and is a compact radio source (André et al. 1988; Hamaguchi et al. 2003; Gagné et al. 2004). However, unlike  $\rho$  Ophiuchi, in Oph S 1 the thick cocoon that shrouds the central objects could have a significant role in shaping the radio and X-ray emission, likely because of the infalling circumstellar material or the interaction of the stellar winds and stellar magnetic field with the surrounding material.

We find even less likely an X-ray variability arising from colliding winds between the two components of the system, given the weak winds expected from the two B2 stars and their separation. A marked dropoff of the X-ray flux is observed around spectral type B1 marking a change in the mechanisms of production of X-rays from stellar winds (Cassinelli et al. 1994; Cohen et al. 1997).  $\rho$  Ophiuchi does not fit into this observational evidence. In this respect, given its relatively close distance,  $\rho$  Ophiuchi is one of the best target for further investigation of any weak X-ray emission from colliding winds originated from the region between the two components of the system.

In summary, we have presented results of the first pointed X-ray observation of the young B-star binary system  $\rho$  Ophiuchi A+B which reveal clear variability on a timescale of a few hours that is likely associated with magnetic activity, with some other low-level flickering possibly present on shorter timescales. These results, along with detections of similar X-ray variability in a few other young B stars, lend support to the presence of magnetic fields in early B stars. However, in the case of Rho Oph AB, X-ray observations at higher spatial resolution are needed to more accurately determine the position of the X-ray centroid relative to the two closely-spaced B star components and to confirm that the X-ray emission is entirely due to the primary.

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